Overview of NSO and Advanced Design Studies

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OFES Budget Meeting

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OFES Headquarters, Germantown

Electronic copy: http://aries.ucsd.edu/najmabadi/TALKS

ARIES Web Site: http://aries.ucsd.edu/ARIES

Contributors to the FIRE Design Study

FIRE is a design study for a major Next Step Option in magnetic fusion and is carried out through the Virtual Laboratory for Technology. FIRE has benefited from the prior design and R&D activities on BPX, TPX and ITER.

Advanced Energy Systems
Argonne National Laboratory
Bechtel Technology and Consulting
General Atomics Technology
Georgia Institute of Technology
Idaho National Engineering Laboratory
Lawrence Livermore National Laboratory
Massachusetts Institute of Technology
Oak Ridge National Laboratory
Princeton Plasma Physics Laboratory
Sandia National Laboratory
Stone and Webster
The Boeing Company
University of Illinois
University of Wisconsin

NSO/FIRE Community Involvement (FY-99)

A Proactive NSO/FIRE Outreach Program has been undertaken to solicit comments and suggestions from the community on the next step.

- Presentations have been made and comments received from:

SOFT/Fr	**Sep 98**	**IAEA/Ja**	**Oct 98**
APS-DPP	**Nov 98**	**FPA**	**Jan 99**
APEX/UCLA	**Feb 99**	**APS Cent**	**Mar 99**
IGNITOR	**May 99**	**NRC**	**May 99**
GA	**May 99**	**LLNL**	**May 99**
VLT-PAC	**Jun 99**	**MIT PSFC**	**Jul 99**
Snowmass	**Jul 99**	**PPPL/SFG**	**Aug 99**
U. Rochester	**Aug 99**	**NYU**	**Oct 99**
U. Wis	**Oct 99**	**FPA**	**Oct 99**
SOFE	**Oct 99**	**APS-DPP**	**Nov 99**
U. MD	**Dec 99**	**DOE/OFES**	**Dec 99**
VLT PAC	**Dec 99**	**Dartmouth**	**Jan 00**
Harvey Mudd	**Jan 00**	**FESAC**	**Feb 00**
ORNL	**Feb 00**	**Northwest'n**	**Feb00**
U. Hawaii	**Feb 00**	**Geo Tech**	**Mar 00**
U. Georgia	**Mar 00**	**PPPL**	**Mar 00**

- **The FIRE web site has been developed to make information on FIRE and fusion science accessible and up to date. A steady stream of about 150 visitors per week logs on to the FIRE web site since the site was initiated in early July, 1999.**

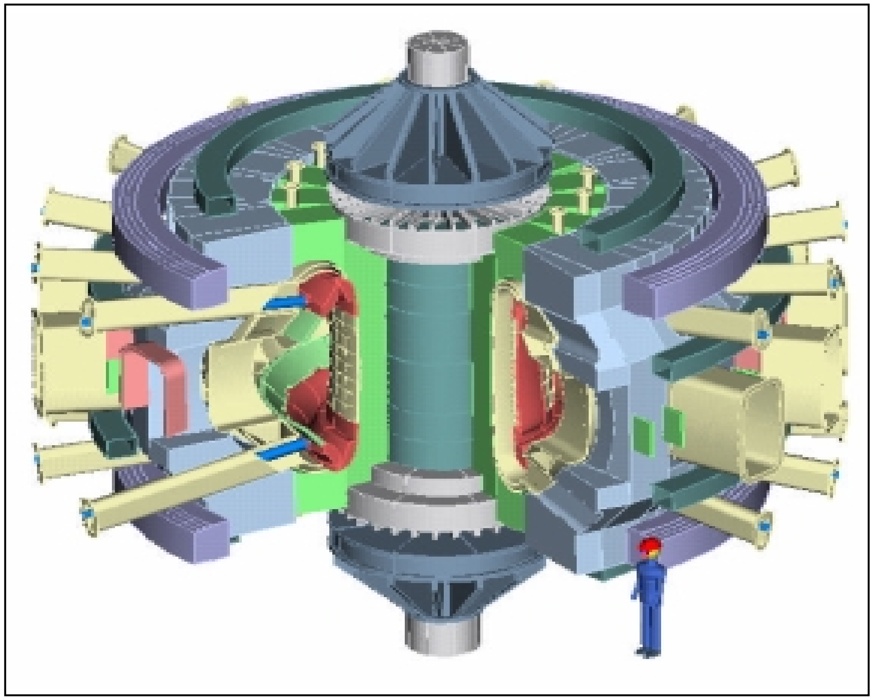
Burning Plasma Physics Objectives for a Fusion Ignition Research Experiment (FIRE)

- Determine the conditions required to achieve alpha-dominated plasmas:
    - Energy confinement scaling with alpha- dominated heating
    - β-limits with alpha- dominated heating
    - Density limit scaling with alpha- dominated heating
- Control alpha- dominated plasmas (e.g., modification of plasma profiles)
- Sustainment of alpha- dominated plasmas - high-power-density exhaust of plasma particles and energy, alpha ash exhaust, study effect of alpha heating on the evolution of bootstrap current profile.
- Exploration of alpha- dominated burning plasma physics in some advanced operating modes and configurations that have the potential to lead to attractive fusion applications.
- Determination of the effects of fast alpha particles on plasma stability.

Attain, explore, understand and optimize alpha-dominated plasmas to provide knowledge for the design of attractive Magnetic Fusion systems.

Fusion **I**gnition **R**esearch **E**xperiment

(FIRE)



Design Goals

- **R = 2.0 m, a = 0.525 m**
- **B = 10 T, (12T)***
- **W_{mag}= 3.8 GJ, (5.5 GJ)***
- **I_p = 6.5 MA, (7.7 MA)***
- **P_{fusion} ~ 220 MW**
- **Q ~ 10, τ_E ~ 0.55s**
- **Burn Time $=$ 21s (12s)***
- **Tokamak Cost ≤ \$0.3B**

  Base Project Cost ≤ \$1B

* Higher Field Option

Attain, explore, understand and optimize alpha-dominated plasmas to provide knowledge for the design of attractive MFE systems.

Flexibility is Critical for the Next Step Facility

- The exploration, understanding and optimization of burning plasma and "long pulse" advanced tokamak physics requires a flexible facility.

- Long-pulse reactor-scale deuterium plasma experiments require remote handling which is also needed for burning plasma experiments.

- FIRE has very many large access ports for diagnostics and heating systems, and the capability to add new systems as they are developed. A comprehensive diagnostic complement has been identified and initial port assignments have been made.

- The scale of FIRE provides adequate performance while the small size will facilitate modification as the experimental program proceeds.

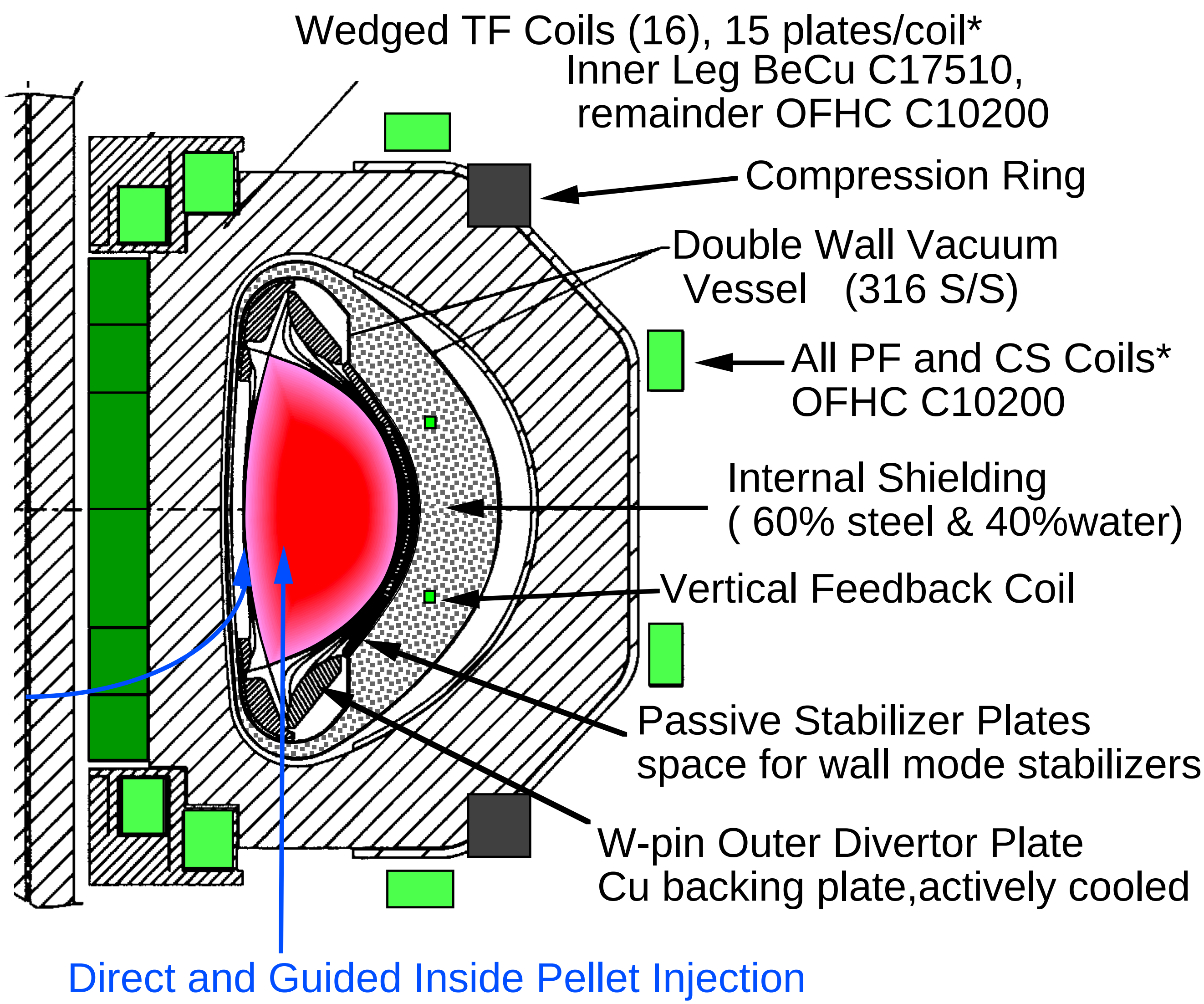
In reality, FIRE also stands for

Flexible Ignition Research Experiment

FIRE Incorporates Advanced Tokamak Innovations

AT Features

- DN divertor
- strong shaping
- very low ripple
- internal coils
- space for wall stabilizers
- inside pellet injection
- large access ports



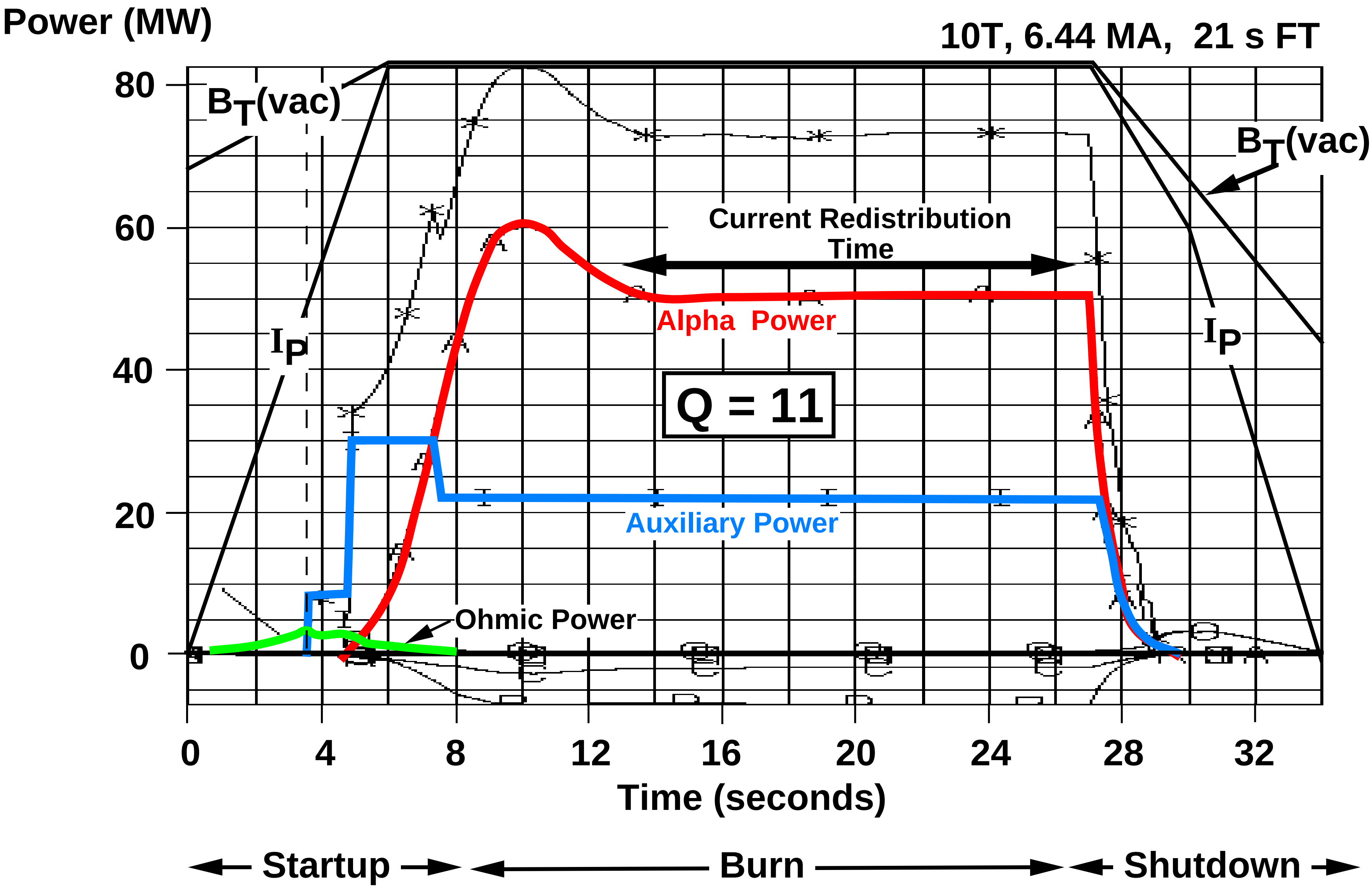
*Coil systems cooled to 77 °K prior to pulse, rising to 373 °K by end of pulse.

A Robust and Flexible Design for FIRE has been Achieved

- Toroidal and poloidal coil structures are independent allowing operational flexibility
    - The toroidal field coils are wedged with static compression rings to increase capability to withstand overturning moments and to ease manufacturing.
- 16 coil TF system with large bore provides
    - Large access ports (1.3m high by 0.7m wide) for maintenance and diagnostics.
    - Low TF ripple (0.3% at plasma edge) provides flexibility for lower current AT modes without large alpha losses due to ripple.
- Double-null divertor configuration for H-mode and AT modes with helium pumping that is maintainable/replaceable/upgradeable remotely
- Double wall vacuum vessel with integral shielding (ITER-like) to reduce neutron dose to TF and PF coils, and machine structure.
- Cooling to LN2 allows full field (10T) flattop for 20s or 4T (TPX-like) flattop for 250s.

The FIRE Engineering Report and 16 FIRE papers presented at the IEEE Symposium on Fusion Engineering are available on the web at http://fire.pppl.gov

1 1/2 -D Simulation* of Burn Control in FIRE



* The Tokamak Simulation Code (TSC) is one of several plasma simulation codes. **Click here http://w3.pppl.gov/topdac/**

FIRE could Access High-Gain Advanced Tokamak Regimes for Long Durations

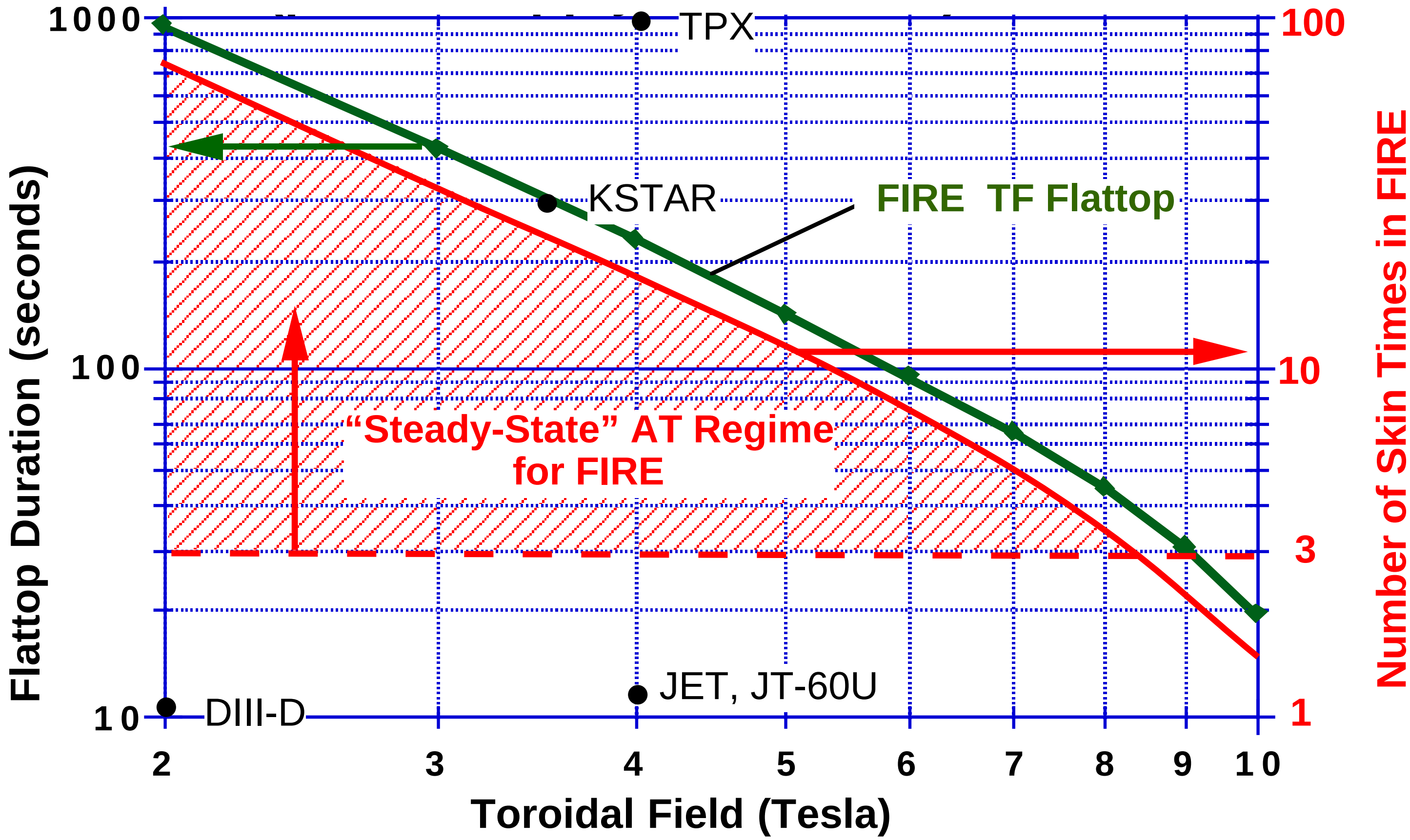
- The coupling of advanced tokamak modes with strongly burning plasmas is a generic issue for all advanced “toroidal” systems. The VLT PAC, Snowmass Burning Plasma and Energy Subgroup B recommended that a burning plasma experiment should have AT capability.

- FIRE, with strong plasma shaping, flexible double null poloidal divertor, low TF ripple, dual inside launch pellet injectors, and space reserved for the addition of current drive (LHCD) and/or a smart conducting wall, has the capabilities needed to investigate advanced tokamak regimes in a high gain burning plasma.

- The LN inertially cooled TF coil has a pulse length capability ~250 s at 4T for DD plasmas. This long pulse - AT capability rivals that of any existing divertor tokamak or any under construction. **The coils are not the limit.**

- Recent AT regimes on DIII-D (Shot 98977) sustained for ~ 16 τ_E serve as demonstration discharges for initial AT experiments on FIRE. Need to develop self-consistent scenarios with profile control on FIRE with durations ~ 3 τ_{skin} .

FIRE can Access "Long Pulse" Advanced Tokamak Modes at Reduced Toroidal Field.



Note: FIRE is ≈ the same size as TPX and KSTAR.
At Q = 10 parameters, typical skin time in FIRE is 13 s and is 200 s in ITER-RC .

The combination of KSTAR and FIRE could cover the range from steady-state non-burning advanced-tokamak modes to "quasi-equilibrium" burning plasmas in advanced tokamak modes.

NSO Funding (k$)

FY99	FY00	FY01A	FY01B	FY02A	FY02B
4100	2660	2660	4000	2660	6000

FY00 Activities

- Complete costing exercise
- Complete preliminary site study
- Develop physics and engineering design to support a technical review this summer
- Organize and brief on NSO PAC

FY01 Plan

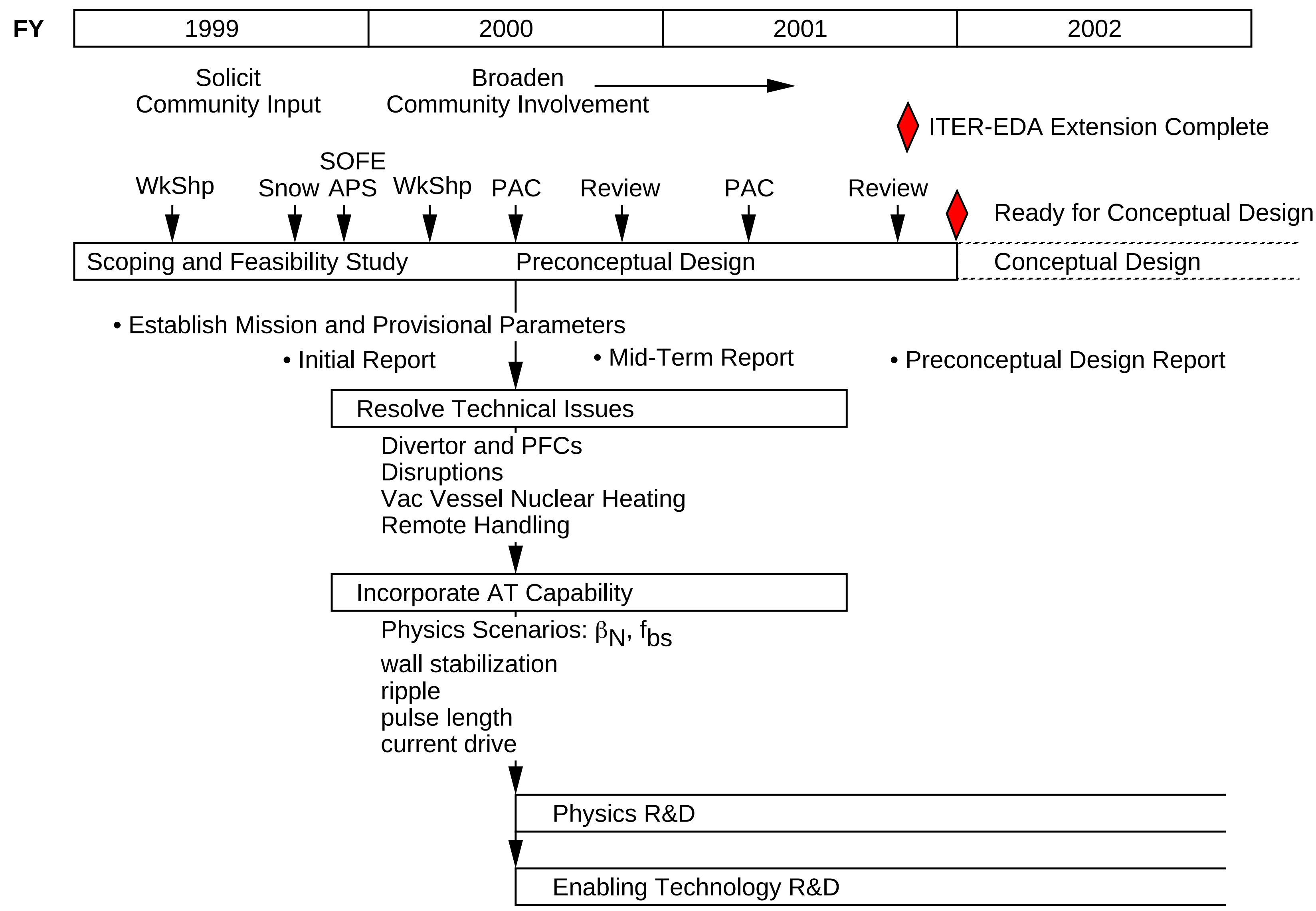
- Proceed with the preconceptual design to support conceptual design initiation in 02 by resolving technical issues:
  - Divertor and PFC heat load
  - Disruption forces
  - Vac vessel nuclear heating
  - Remote handling

- While incorporating AT capability:
  - Wall stabilization
  - Reduced ripple
  - Increased pulse length
  - Current drive

FY02 Plan

- Begin conceptual design

Basic Strategy for an Advanced Tokamak Next Step (FIRE)



Critical Issues for FIRE and Magnetic Fusion.

The critical physics and engineering issues for FIRE are the same as those for fusion, the goal of FIRE is to help resolve these issues for magnetic fusion. The issues and questions listed below need to be addressed in the near future.

- Physics
  - confinement - H-mode power threshold, edge pedestal, AT modes,
  - stability - NTMs, RWM, disruptions: conducting wall? feedback coils?
  - heating and current drive - ICRF is baseline: NBI & LHCD as upgrades?
  - boundary - detached divertor operation, impurity levels, confinement
  - self-heating - fast alpha physics and profile effects of alpha heating

  Development of self-consistent self-heated AT modes with external controls

- Engineering
  - divertor and first wall power handling (normal operation and disruptions)
  - divertor, first wall and vacuum vessel for long pulse AT modes
  - evaluate low inventory tritium handling possibilities
  - complete many engineering details identified in FIRE Engineering Report
  - evaluate potential sites for Next Step MFE experiment
  - complete cost estimate for baseline, identify areas for cost reduction

Major Conclusions of the FIRE Design Study

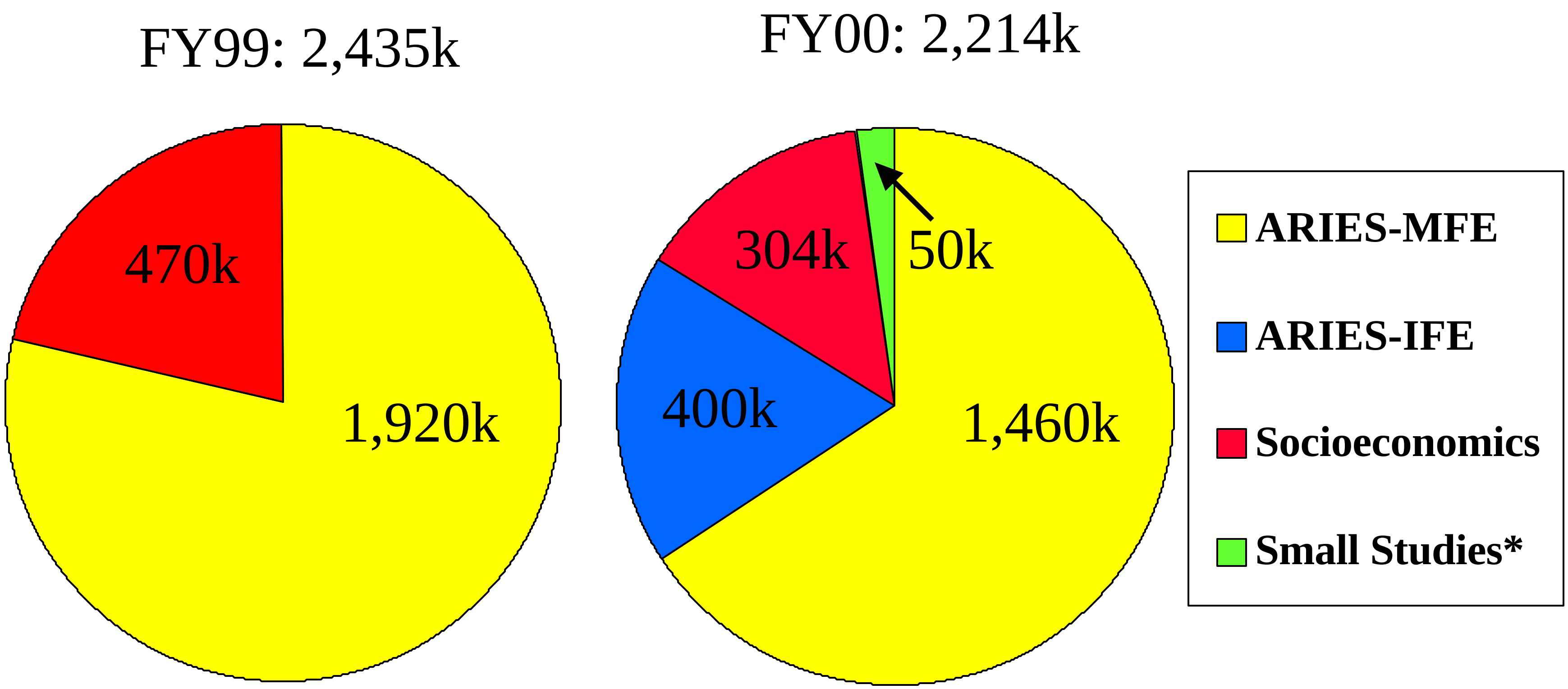
- Exploration, understanding and optimization of alpha-dominated (high-gain) burning plasmas are critical issues for all approaches to fusion.

- The tokamak is a cost-effective vehicle to investigate alpha-dominated fusion plasma physics, and its coupling to advanced toroidal physics for MFE. The tokamak is technically ready for a next step to explore fusion plasma physics.

- The FIRE compact high field tokamak can address the important alpha-dominated plasma issues, many of the long pulse advanced tokamak issues and begin the integration of alpha-dominated plasmas with advanced toroidal physics in a $1B class facility.

- A plan is being developed for an Advanced Tokamak Next Step that will address physics, engineering and cost issues in FY 2000-1 with the goal of being ready to begin a Conceptual Design in 2002. Funding increments are needed in FY01 and 02 to support this schedule.

Distribution of Advanced Design Research



* Traditionally, ~10% of total effort have been for "small studies" of exploratory concept (awarded based on peer review). These studies were eliminated (plus reduction in ARIES program) in FY99 to launch the socioeconomic research.

Socioeconomic Studies: FY99 & FY00 Research

- Most of the socioeconomic studies were launched in FY 99:

  Study of options to deploy large fusion power plant including hydrogen production and co-generation. (ORNL & Partners). Completed in 12/99.

  Establish the merits and address issues associated with fusion implementation (PPPL).

  Macro-economics modeling of global energy market and role of fusion (PNL) (Continuation of previous work).

  Comparison of various sources of energy based on equivalent CO_2 emission (U. Wisc.).

Extra

Socioeconomic Studies: Planning for FY 01

- Four separate socioeconomic studies were launched in FY 99. An overview of these studies was presented to VLT PAC in Dec. 1999. (see http://aries.ucsd.edu/najmabadi/TALKS)

- Plans for a coordinated national activity focused on making fusion visible in the energy planning and forecasting circles were presented to the PAC.

- PAC recommendation: "The PAC contains a variety of views on this initiative. Hence, we recommend that the socioeconomic study be initiated on a smaller scale than that proposed. This can demonstrate, on a small scale, the feasibility of penetration into the energy community, and thereby lay the basis for implementation of the full plan. The smaller scale effort should be clarified at our next meeting, and work should be allocated according to competitive peer review "

How to Make a Case for Fusion -- A Strategy

- Present activities are too small to make much impact. Connection to energy forecasting scientists and circles does not exist.
- In order to make a case for fusion, sufficient investment has to be made or we will always remain outside of these circles.
- It takes a coordinated national activity focused on making fusion visible in the energy planning and forecasting circles.
  - 3 to 5 FTP level of effort (500 to 800k), consisting of part-time activities from several scientists from major fusion institutions.
  - National effort should lead to a consensus view rather than highlighting advocacy group positions.
  - Establish credibility and expertise through high-quality research and publishing papers in scientific journals of this field.
  - Establish a circle of scientists that attend all major conferences/symposia in energy forecasting field.

Extra

National Power Plant Studies Program (ARIES) Initiated Two-years Projects in 1/99

- **Fusion Neutron Source Study:** **(In Documentation)**
  - Context: Non-electric applications of fusion, specially those resulting in near-term products may lead to new clients and to additional resources for fusion.
  - A concept definition study was performed to identify promising concepts and provide necessary information for proceeding further. Results were presented at Jan. FESAC meeting.
- **ARIES-AT:** **(To be completed in 2000)**
  - Assess impact of advanced technologies as well new physics understanding & modeling capabilities on the performance of advanced tokamak power plants.
- **Integrated IFE Chamber Study:** **(Start in 4/00)**
  - Identify and explore design window for IFE chambers.

ARIES-RS Study Sets the goals and Direction of Research for ARIES-AT

	ARIES-RS Performance	ARIES-AT Goals
Economics		
Power Density	Reversed-shear Plasma Radiative divertor Li-V blanket with insulating coatings	Higher performance RS Plasma, High T_c superconductors
Efficiency	610^o C outlet (including divertor) Low recirculating power	> 1000^o C coolant outlet > 90% bootstrap fraction
Availability	Full-sector maintenance Simple, low-pressure design	Same or better
Manufacturing		Advanced manufacturing techniques
Safety and Environmental attractiveness	Low afterheat V-alloy No Be, no water, Inert atmosphere Radial segmentation of fusion core to minimize waste quantity	SiC Composites Further attempts to minimize waste quantity

Extra

Main Features of ARIES-AT^2
(Advanced Technology & Advanced Tokamak)

- **High Performance Very Low-Activation Blanket:** Innovative high-temperature SiC composite/LiPb blanket design capable of achieving ~60% thermal conversion efficiency with small nuclear-grade boundary and excellent safety & waste characterization.
- **Higher Performance Physics:** Reversed-shear equilibria have been developed with up to 50% higher than ARIES-RS and reduced current-drive power.
- **Higher Performance Magnets:** High-T_c superconductors.

  Present strawman operates at the same power density as ARIES-RS, higher was used to reduce the peak field at the magnet.
- Reduce unit cost of components through **advanced manufacturing techniques.**

ARIES-AT^2: Physics Highlights

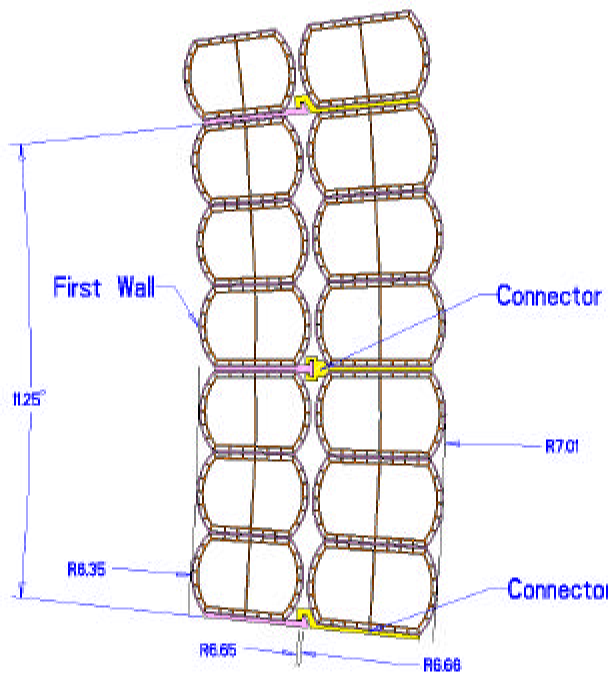
- Use the lessons learned in ARIES-ST optimization to reach a higher performance plasma;
  - Using > 99% flux surface from free-boundary plasma equilibria rather than 95% flux surface used in ARIES-RS leads to larger elongation and triangularity and higher stable .
- Eliminate HHFW current drive and use only lower hybrid for off-axis current drive.
- Perform detailed, self-consistent analysis of plasma MHD, current drive and divertor (using finite edge density, finite p , impurity radiation, etc.)
- ARIES-AT blanket allows vertical stabilizing shell closer to the plasma, leading to higher elongation and higher .

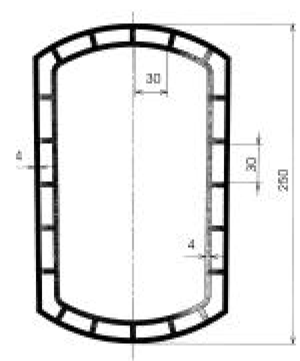
Extra

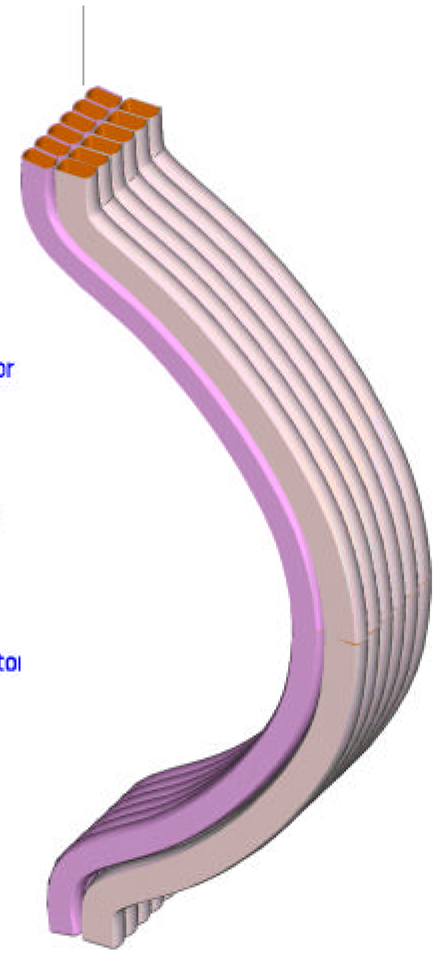
ARIES-AT^2: SiC Composite Blankets

- Simple, low pressure design with SiC structure and LiPb coolant and breeder.
- High LiPb outlet temperature (~1100^{o}C) and high thermal efficiency of ~60%.
  - * Maximum SiC structure temperature 1000^{o}C;
  - * Maximum SiC structure/LiPb interface temperature 900-940^{o}C.
- Simple manufacturing technique.
- Very low afterheat.
- Class C waste by a wide margin. Qualifies for Class A after ~30 years.

Outboard blanket & first wall







Extra

Major Parameters of ARIES-RS and ARIES-AT

	ARIES-RS	ARIES-AT
Aspect ratio	4.0	4.0
Major toroidal radius (m)	5.5	5.2
Plasma minor radius (m)	1.4	1.3
Plasma elongation ($_x$)	1.9	2.2
Plasma triangularity ($_x$)	0.77	0.86
Toroidal	5%	9.2%
Electron density (10^{20} m^{-3})	2.1	2.25
ITER-89P scaling multiplier	2.3	2.7
Plasma current	11	13

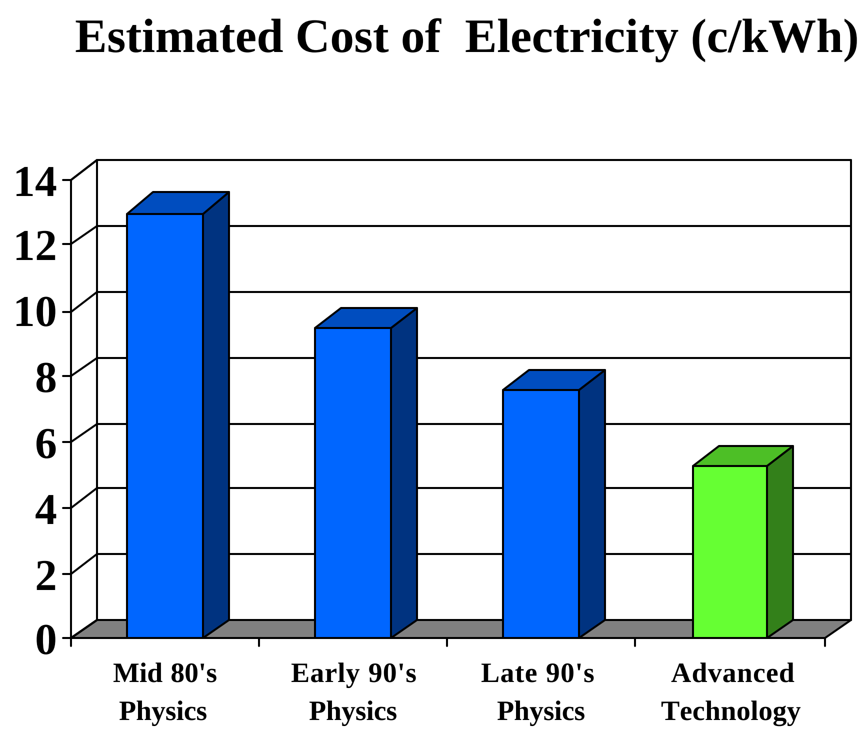
Extra

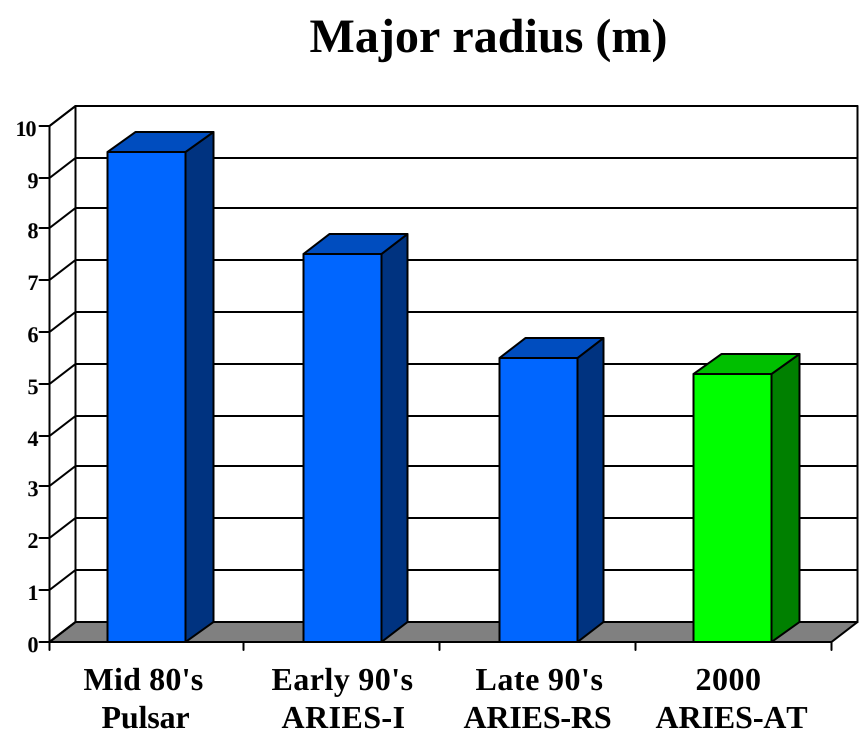
Major Parameters of ARIES-RS and ARIES-AT

	ARIES-RS	ARIES-AT
On-axis toroidal field (T)	8	6
Peak field at TF coil (T)	16	11
Current-drive power to plasma (MW)	81	25
Peak/Avg. neutron wall load (MW/m^2)	5.4/ 4	4.7/3.8
Fusion power (MW)	2,170	1,720
Thermal efficiency	0.46	0.59
Gross electric power (MW)	1,200	1,136
Recirculating power fraction	0.17	0.12
Cost of electricity (mill/kWh)	76	53

Extra

Our Vision of Magnetic Fusion Power Systems Has Improved Dramatically in the Last Decade, and Is Directly Tied to Advances in Fusion Science & Technology



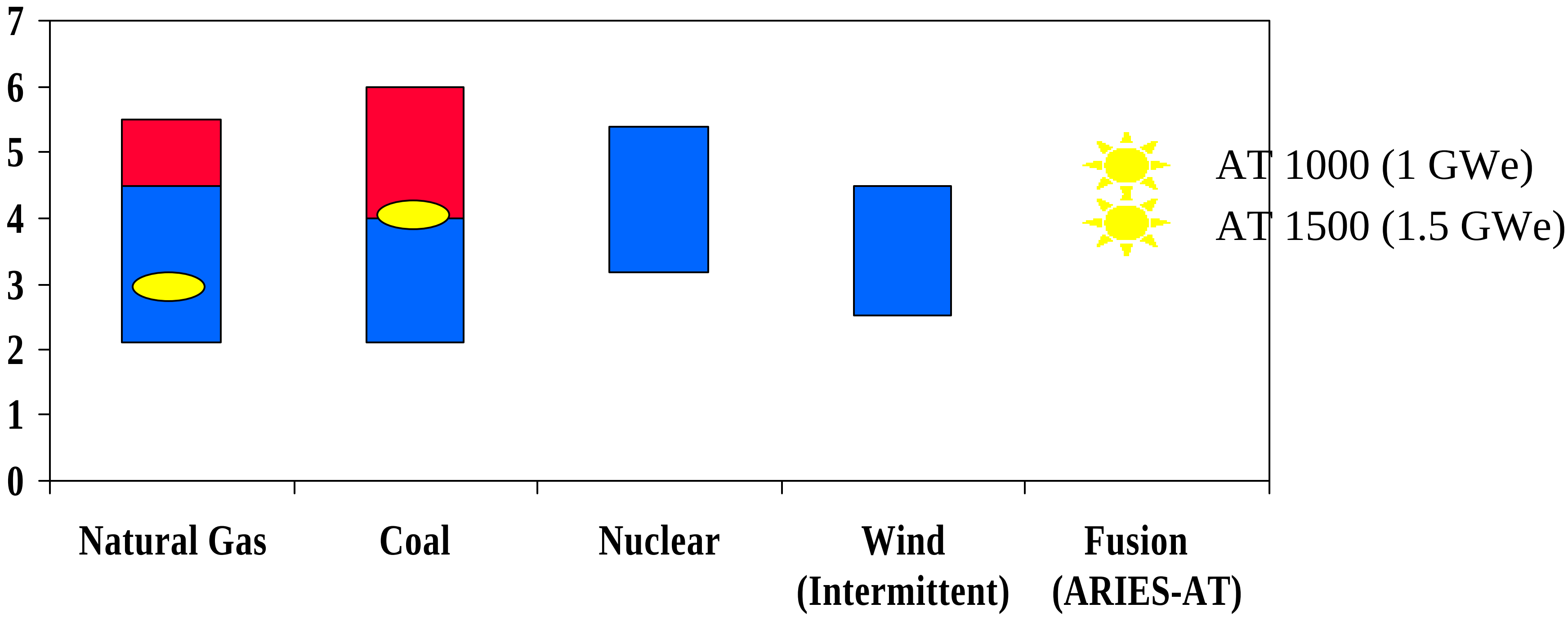


Present ARIES-AT parameters:

Major radius:	5.2 m	Fusion Power	1,720 MW
Toroidal :	9.2%	Net Electric	1,000 MW
Wall Loading:	3.8 MW/m^2	COE	5.3 c/kWh

ARIES-AT is Competitive with Other Future Energy Sources

Estimated range of COE (c/kWh) for 2020*



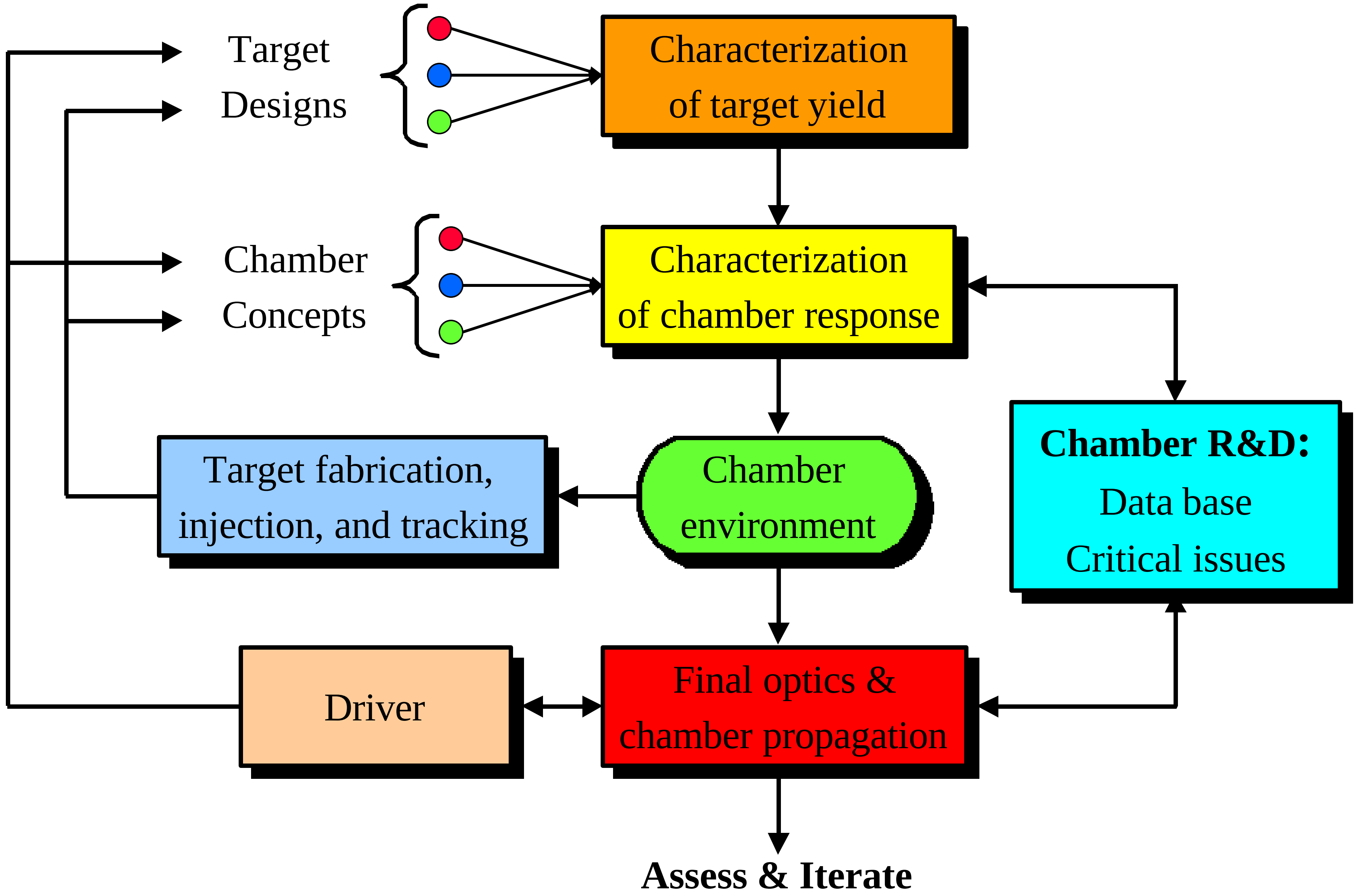
EPRI Electric Supply Roadmap (1/99):

- Business as usual
- Impact of $100/ton Carbon Tax.

Estimates from Energy Information Agency Annual Energy Outlook 1999 (No Carbon tax).

* Data from Snowmass Energy Working Group Summary.

The Integrated IFE Study Will Identify and Explore the Design Window for IFE chambers & Define R&D Needs

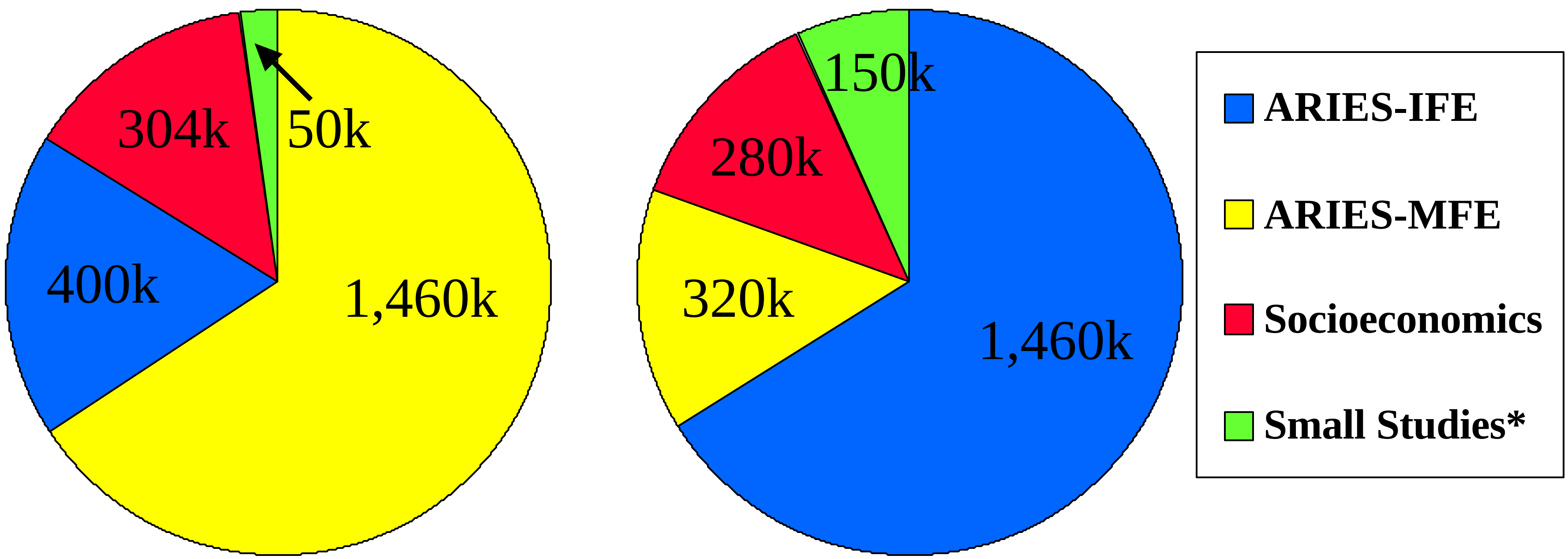


Advanced Design Plans for FY01: President’s Budget (2,210k)

- President’s budget level does not match SEAB and FESAC directions of conducting both IFE and MFE advanced design studies. The deliverables below assume focus ONLY on IFE studies with a small portion of funds devoted to keep the MFE expertise viable for later examination of MFE systems.
- Tasks under President’s budget levels:
  1. Assessment of IFE chambers and identification of the respective design window to guide IFE technology and driver programs.
  2. Collaboration with the European power plant studies program and enhancement of analysis tools for MFE power plants.
  3. Socioeconomic studies of fusion energy.
  4. Smaller studies of exploratory concepts

Distribution of Advanced Design Research President's Budget (2,210k)

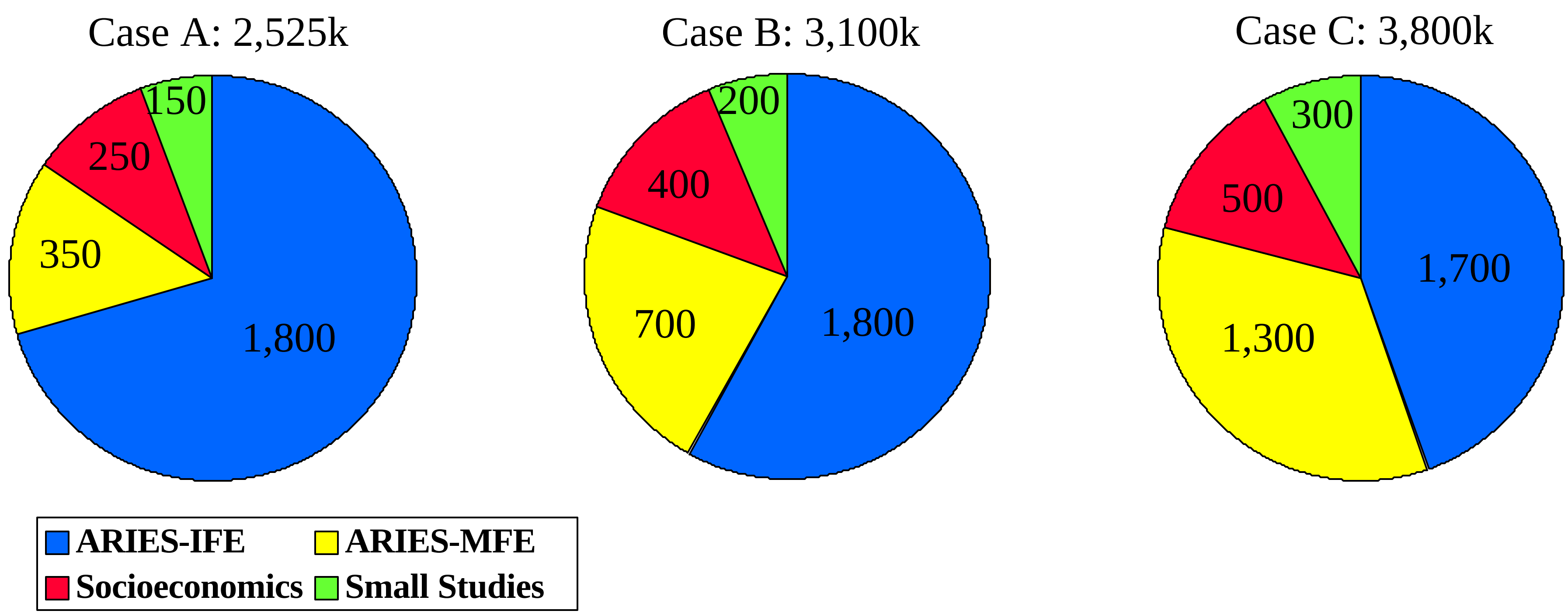
FY00: 2,214k FY01: 2,210k



Issues:

1) Under-funded ARIES-IFE study;
2) ARIES-MFE expertise on hold;
3) Socioeconomic studies on hold.

Expected Deliverables for Three Budget Increments



Case A
1. Cost-effective IFE Study
2. MFE Studies on hold
3. Socioeconomic on hold

Case B
1. Cost-effective IFE Study
2. Start on MFE PoP concepts
3. Start on socioeconomic

Case C
1. Cost-effective IFE Study
2. Cost-effective MFE study
3. Healthy socioeconomic research

Budget Planning Activities Last Year Has Helped in Developing Many Budget Scenarios.

	FY99 Advanced Design	2,435k
2/99	FY00 President's Budget	2,950k
8/99	Aug. Fin Plan (Senate Number)	2,500k
9/99	OFES Plan (House Number)	3,300k
11/99	OMB revisions	2,214k